Biological recycling of bio-waste and compost utilization from a life cycle perspective

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Abstract In order to set a reference inventory data, an extensive literature search on compost production and compost utilization has been performed. The aim is to define carbon and energy footprint of bio-waste recycling and compost utilization. The available data suggest that when bio-waste is properly collected and recycled (through composting or anaerobic digestion) and a high quality compost is produced and used, valuable environmental benefits can be achieved. In particular, the recycling of 1 tonne bio-waste generates GHG emissions that range from -0.3 up to ~0.1 tonne CO_2 equivalents (i.e. eq.), whereas the consumption of fossil resources ranges from -4.4 up to 0.5 GJ eq. depending on the bio-waste recycling technology and compost utilization considered.

1 Introduction

Bio-waste (i.e. kitchen and yard waste) represents a critical fraction of Municipal Solid Waste (MSW) for the following reasons: it is the largest fraction, on average ranging from 30 to 40% of MSW across Europe [1]; its management is not easy due to odours and the production of leachate; if disposed of in landfill, bio-waste produces methane, a powerful greenhouse gas; in case of incineration, its high water content affects energy recovery. In order to reduce the environmental impact of bio-waste and meet the Landfill Directive 99/31/EC, the separate collection of bio-waste has become a priority for many local authorities. According to Barth et al. [2], in 2005 almost 24 Mio tonne of bio-waste were biologically recycled in the EU i.e. about 50 kg per capita out of 160 kg, the theoretical maximum amount. This means that bio-waste collection has substantial room for improvement with positive consequences for landfill management and incineration with energy recovery.

Bio-waste is recovered by organic recycling, i.e. composting or anaerobic digestion followed by composting (i.e.AD). Compost is a soil improver: it contains nutrients and humic carbon and improves overall soil quality [3]. Some of these beneficial effects can be assessed with LCA methodology others, unfortunately, not yet. This paper provides factual information about the carbon and energy footprint of bio-waste recycling and compost utilization from a life cycle perspective.

2 Research objective

The objective of this study was to assess the carbon and energy footprint of bio-waste recycling and compost utilization. Two main biological treatments were considered: enclosed industrial composting and dry anaerobic digestion followed by indoor composting.

3 Methodology

Life cycle thinking (LCT) approach has been used. All relevant life cycle stages related to the life cycle of compost starting with bio-waste acquisition (collection excluded) and through to the final use of compost were analysed using the LCA methodology.

4 The LCA

The Functional Unit (i.e. F.U.) is defined as "The biological treatment of 1 tonne of bio-waste and compost utilization". A simplified process flow diagram of the analyzed systems is shown in Fig. 1.

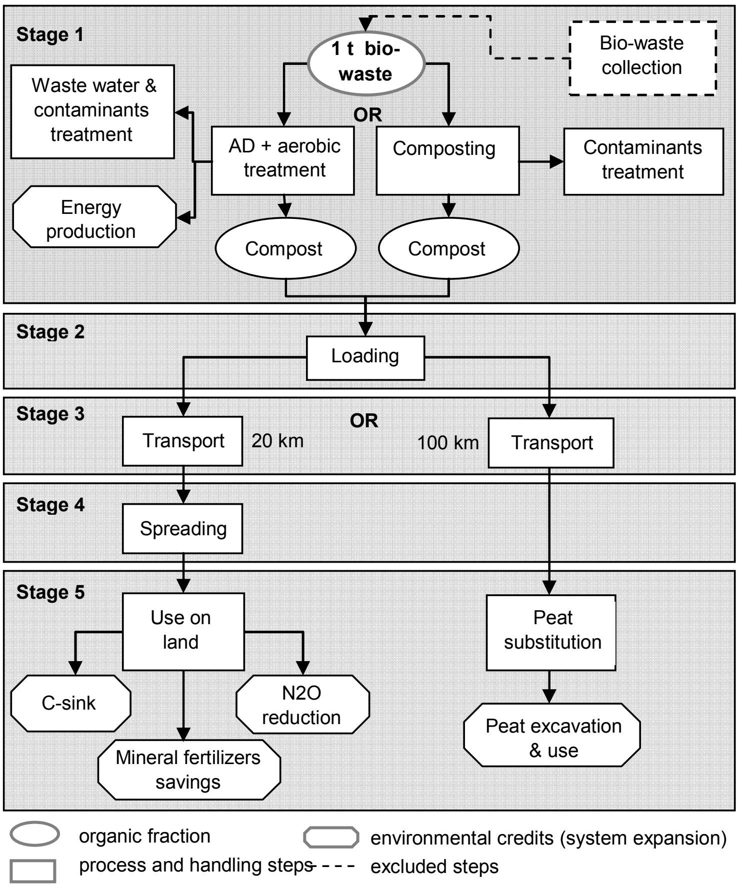

Fig.1: Simplified flow diagram of the studied systems (t= tonne)

Two main technologies for bio-waste recycling were considered: enclosed composting and dry thermophilic anaerobic digestion followed by indoor composting. The compost produced was assumed to be used in agriculture and in growing media. The inventory data of bio-waste are shown in Tables 1 to 5. Each table shows the range of values found in the analysed sources and the selected values used in this study. The values were selected either by picking the typical value when the sources were concordant or when the sources were contrasting as the average between the minimum and maximum. Infrastructure, transport, electricity and materials production, such as mineral fertilizers and diesel etc. come from Ecoinvent v 2.2 database [4] and reflect the European context.

Tab.1: Data inventory for Stage 1. a) composting b) anaerobic digestion. All the data are referred to 1 tonne of fresh bio-waste treated

a)

Composting		**Range**	**Selected value**	**Source**
Average process yield [%]		10 - 50	40	[5,6,7]
Technosphere Input	Diesel [l]	0.13 - 3.60	1.9	[6,7]
	Electricity [MJ]	32.4 - 342	187	[5,6,7]
	Infrastructure [p][1]	$3x10^{-6}$	$3x10^{-6}$	[4]
Direct GHG emissions	CH_4 [kg]	0.02 - 1.80	0.9	[7]
	N_2O [g]	10 - 120	65	[7]
Contamination	Amount [kg]	~0 - 250	80	[4,5,6,7]
	Composition	not specified	composition[2]	[8]
	End of life[3]	70% landfill + 30% incineration		[9]

b)

Anaerobic Digestion		**Range**	**Selected value**	**Source**
Average process yield [%]		30 - 40	30	[4,10]
Technosphere Input	Diesel [l]	not significant	0.50	[10]
	Electricity [MJ]	not significant	200	[10]
	Infrastructure [p][1]	not specified	$1.4*10^{-6}$	[4]
Wastewater treatment	[m3]	~0 - 0.47	0.4	[5,10]
Biogas production	Nm3	112 -187	150	[5,10]
Net electricity output	MJ	432 -641	537	[5,10]
Contamination	Amount (kg)	50 -150	100	[10]
	Composition	not specified	composition[2]	[8]
	End of life[3]	70%landfill + 30% incineration		[9]

[1] p= "parts" of the infrastructure needed for treating 1 tonne of bio-waste;

[2] 67.2% plastic, 4.9% glass, 4.6% metals, 2.5% inert, 20.8% other;

[3] EU27 average in 2008.

It is important to point out that most sources neglect both the amount and the composition of contaminants, i.e. the non compostable fractions (plastic, metal, glass, etc) that contaminate bio-waste even though they can generate significant GHG emissions. In this study contamination has been taken into consideration on the basis of a study [8] which, based on 964 analysis, provided a detailed and representative composition.

Tab. 2 Compost characteristics.

Parameter	Unit	Range	Selected value	Source
Dry Matter (DM)	% on ww	28 - 74	60	[5,11,12,13,14]
Organic Carbon	% on DM	19 - 47	25	[5,7,12]
N	% on DM	0.9 - 2.8	1.8	[5, 7,11,12,13,14]
P (as P_2O_5)	% on DM	0.4 - 2.1	1.3	[5, 7,11,12,13,14]
K (as K_2O)	% on DM	0.4 - 3.0	1.7	[5, 7,11,12,13,14]
Ca (as CaO)	% on DM	3.4 - 11.8	7.6	[5,13]
Mg (as MgO)	% on DM	0.6 - 1.72	1.2	[5,13]

ww = wet weight

The characteristics of compost (Table 2) are important since they affect compost use and ultimately the environmental benefits associated with its utilization. All the sources refer to high quality compost derived by source separated food waste, sometimes mixed with municipal garden waste. Compost and post-treated digestate are assumed to have same characteristics, because of the similar contents of organic matter and nutrients [13,15,16].

Compost ready for final use is presumed to be directly loaded at the production plant and then transported to the final destination. The inventory data and the utilized sources are shown in Table 3.

Tab. 3 Data inventory for Stages 2-3-4. All data are referred to 1 tonne of fresh bio-waste treated.

Stage		Use on land	Peat substitution	Source
Loading	l diesel/t wet compost	0.4	0.4	[4,17]
Transport	Km	20 (tractor&trailer)	100 (lorry > 16t)	[4,17,18]
Spreading	t wet compost	0.3/0.4 [4]	none	[4]

t = tonne; [4] Depending on the biological treatment scenario.

Diesel consumption for loading are derived from literature whereas the environmental loads were based on Ecoinvent 2.2 database for production and combustion of a diesel engine. Distances and type of transport are based on the final application of compost. Compost spreading (i.e. use on land only) is carried out with a hydraulic loader and spreader whose data come from Ecoinvent 2.2.

The use on land is one of the most diffused applications for high quality compost and it is normally suitable for extensive full field crops such as wheat, barley, maize and other cereals, sunflower, potatoes and sugar beet [18]. Table 4 shows only the benefits of compost use that can be easily quantified with an LCA. Other properties (e.g. soil biodiversity improvement) can not be properly quantified in an LCA.

Tab.4: Inventory data for Stage 5 - compost use on land

Benefits			Unit	Range	Selected value	Source
Nutrients supply	N	Supply	kg/t wet compost	5.2 -16.8	11.0	[6]
		S.E.[5]	%	10 - 60	35	[7,17]
	P2O5	Supply	kg/t wet compost	2.3 -12.8	7.6	[6]
		S.E.[5]	%	38 -100	70	[17]
	K2O	Supply	kg/t wet compost	2.46 -18.2	10.4	[6]
		S.E.[5]	%	80-100	90	[17]
	CaO	Supply	kg/t wet compost	20.3-70.7	45.5	[6]
		S.E.[5]	%	-	100	[15]
	MgO	Supply	kg/t wet compost	3.6 -10.3	6.95	[6]
		S.E.[5]	%	-	100	[15]
C-sink			% on total OC	2 -14	8	[7,18]
N_2O reduction			g/t wet compost	-20 - -201	-110	[7]

t = tonne; [5] Substitution Efficiency; [6] See Table 2.

In Table 4 the supply and the corresponding substitution efficiency (i.e.S.E.) are shown for each nutrient. S.E. is the mineralization level of nutrients contained in compost. For example, a S.E. of 30% indicates that only 30% of the element contained in compost will be available for plants. This parameter is important for calculating the effective mineral fertilizer replacement caused by compost. Furthermore, different types of fertilizers vary significantly in their Carbon and Energy footprint thus, to properly quantify the environmental credits generated by their partial substitution by compost, a realistic scenario was set. To this end the statistical data on N and K fertilizers consumption in the EU 27, provided by Fertilizers Europe [19-22], were elaborated so as to reflect as much as possible a real replacement. For P fertilizers their substitution scenario was handled considering an equal amount of five types of P-fertilizers (i.e. 20% each) coming from Ecoinvent 2.2 database.

The carbon-sink effect is related to the amount of biogenic C contained in compost which remains unmineralized after 100 years. Finally, N_2O emissions reduction is related to the partial substitution of a readily available source of N (i.e. N fertilizers) with a slow-release one (i.e. compost). This avoids the creation of an excessive N pool in soil and, in turn, decreases N_2O formation [7]. Compost can also be used as peat substitute in the preparation of growing media for horticulture, thus avoiding fossil emissions from the excavation, transport and use of peat. Peat is well know as a fossil material that during its mineralization produces fossil CO_2. Nowadays about one quarter of the extracted peat in EU (i.e. about 18 million tonnes per year) is used for the growth media preparation [24], the remaining amount is exploited for energy production in power station.

The substitution factor for peat replacement by compost is based on the conservative method Volume/Volume [7].

Tab.5: Inventory data for Stage 5 - compost use as peat substitution

Benefits	Unit	Range	Selected value	Source
Peat excavation	t/t wet compost	0.2 - 1	0.6	[7,10,16]
Peat transport	km	-	1000	[10]
Peat use [7]	t CO_2 fossil	-	0.82 [8]	[25]

t = tonne; [7] i.e. mineralization of fossil-C; [8] It refers to 0.6 tonne of used peat.

5 Results and discussion

In Table 6 the overall Carbon and Energy footprint related to the recycling of 1 tonne bio-waste are shown.

Tab.6: Carbon and energy footprint related to 1 tonne bio-waste biological recycling and compost utilization

	Bio. Treat.	loading	transport land use	transport peat sub.	spreading on land	Land use	Peat sub.	Total-land use	Total-peat sub.
	Carbon footprint [kg CO_2 eq.]								
Comp.	131	0.5	2.5	5.3	1.3	-74	-364	62	-227
AD	-22	0.4	1.9	4.0	1.0	-55	-273	-74	-291
	Energy footprint [MJ eq.]								
Comp.	799	7	38	86	20	-317	-3700	547	-2808
AD	-1700	5	29	65	15	-238	-2775	-1889	-4405

sub.= substitution

The biological treatments and compost utilization, whose contribution analysis is shown in Fig.2, dominate the carbon and energy footprint of bio-waste recycling. AD represents the best option: whatever the compost utilization, AD biological treatment got environmental benefits (i.e. negative “Cradle to grave” values) both for Carbon and Energy footprint. This is due to the fact that both electricity and compost can be obtained through AD. GHG emissions of composting are lower than those originated by landfilling which account for 0.7 kg CO_2 eq./kg bio-waste [26]. The maximum benefit from compost utilization is achieved when it replaces peat.

Contribution analysis for composting (Fig. 2 Stage 1, first column on the left) indicates that treatment of contaminants generates significant GHG emissions (even if it is often not accounted for in inventory), followed by direct emissions (i.e. CH_4 and N_2O) and electricity consumed by the process. The direct emissions for AD were negligible since it was assumed that all the biogas produced (i.e. CH_4 and CO_2) is completely captured and used for producing electricity.

Contamination of bio-waste affects process yield. A sensitivity analysis has shown that if contaminants reach 25%, the process yield reduces from 40% to 10% and this in turn makes the carbon and energy footprint twice as worse compared to default values. Besides that, a reduction of environmental benefits due to a lower amount of compost produced will occur. Environmental impacts of AD mainly come from electricity consumption and contaminant disposal. However, they are outweighed by the renewable electricity generated using the produced biogas.

The main benefits of compost "use on land" for Carbon and Energy footprint are represented by fertilizer replacement followed by carbon sink and N_2O reduction. When compost is used in growing media the most important avoided impacts are those related to the peat (a non renewable resource) use (for carbon footprint) and peat excavation (for energy footprint). Peat transport can be relevant as well, depending on distance and type of transport. Land use change caused by peat excavation was not accounted for, because the relevant methodology is still not fully developed. However, the GHG emissions from excavation are expected to be relevant.

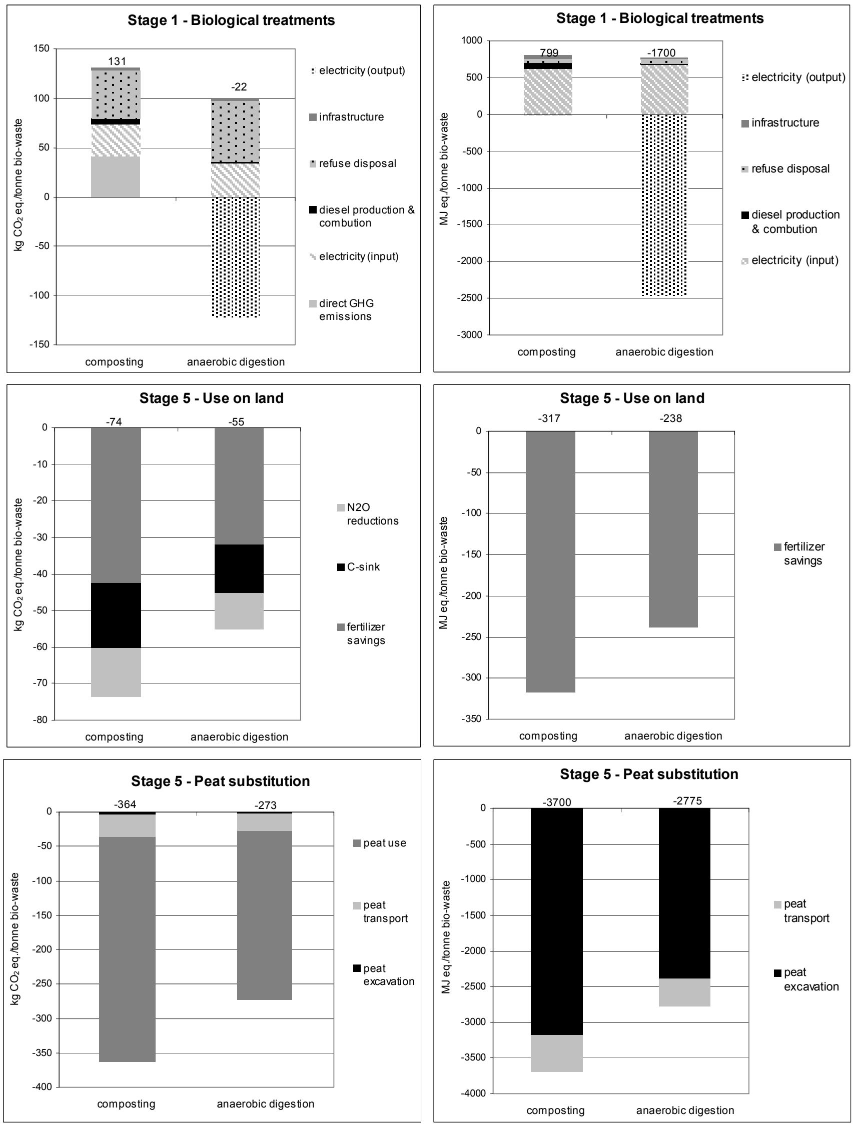

Fig.2: Contribution analysis of biological treatments (i.e. Stage 1) and compost utilization (i.e. Stage 5)

6 Conclusions

Recycling of bio-waste produced by households has substantial room for improvement: currently only 1/3 is recycled whereas 2/3 ends up to landfill or incineration. In 2005 bio-waste collected in the EU27 accounted for about 24 million of tonnes (i.e. about 50 kg bio-waste per capita). When bio-waste is properly recycled (through composting or AD) and high quality compost is produced and used, valuable environmental benefits can be achieved. In particular, the recycling of 1 tonne bio-waste generates an overall GHG emission that ranges from -0.3 up to ~0.1 tonne CO_2 eq., whereas fossil resources consumption ranges from -4.4 up to 0.5 GJ eq. depending on biological treatment and compost utilization. Organic recycling can therefore reduce the amount of waste which is currently sent to landfill or incineration and improve the environmental impacts of waste management. Best results are obtained if bio-waste is homogeneous and the level of contaminants is low. So, in order to achieve good environmental outcomes, it is necessary that all actors of the system (i.e. waste chain) actively collaborate. The quality of bio-waste depends on the behaviour of citizens. If bio-waste is contaminated (mainly by plastics) the direct consequences are:

- High quantities of waste are produced by the composting plant: up to 0.25 tonne per tonne bio-waste in input. From an environmental point of view, the disposal of such amount can have a significant impact.
- Decrease of the composting process yield: up to 10% instead of 40% (average yield for composting plants).
- Decreased compost quality which in turns can compromise its use on land or as a peat substitute.

Collection systems were not analyzed in this study. Some studies point out that the way in which waste is collected influences the amount and the quality of bio-waste and the process yield. For example, according to a case study [27], the door to door source separate collection of bio-waste, using biodegradable bags, decreases the presence of pollutants to a minimum.

High quality compost utilization provides valuable environmental benefits (e.g. fertilizers displacement, C-sink etc.) as demonstrated by this research. However, many other positive features of compost can not be easily evaluated by means of LCA (e.g. increased organic matter content in soil, erosion reduction, ease of tilling etc.). Such aspects are, in the long term, extremely important for sustainable development. It is also worth noting that if all the bio-waste produced in Europe was converted into high quality compost still this amount would be totally absorbed by the potential European market for soil conditioners. On the other hand, the same would replace by far the peat used in the growing media sector [24]. The relevance of this utilization is related to the fact that peat lands constitute an important stock of fossil carbon and their exploitation causes carbon losses [23].

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